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Krauss

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(54) **PUMPJACK PRODUCTION CONTROL**

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E21B 47/00 (2012.01)

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USPC **166/250.15**; 166/369; 166/53; 417/20

(58) **Field of Classification Search**
CPC E21B 43/00; E21B 43/12; E21B 44/00; E21B 47/0008
USPC 166/369, 53, 250.15; 417/53, 12, 20, 417/36, 44.1
See application file for complete search history.

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(57) **ABSTRACT**

A method, software, and apparatus for controlling a pump configured to pump liquid out of a well. Such control may involve determining whether a production rate of gas from the well is increasing, decreasing, or steady, and whether to switch the pump between an OFF state and an ON state. Whether the pump is switched may depend upon whether the production rate of the gas is determined to be increasing, decreasing, or steady.

18 Claims, 6 Drawing Sheets

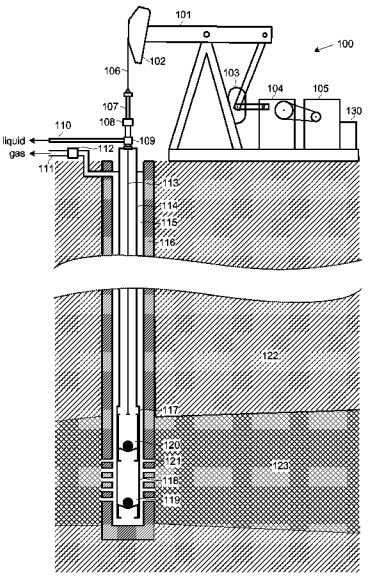
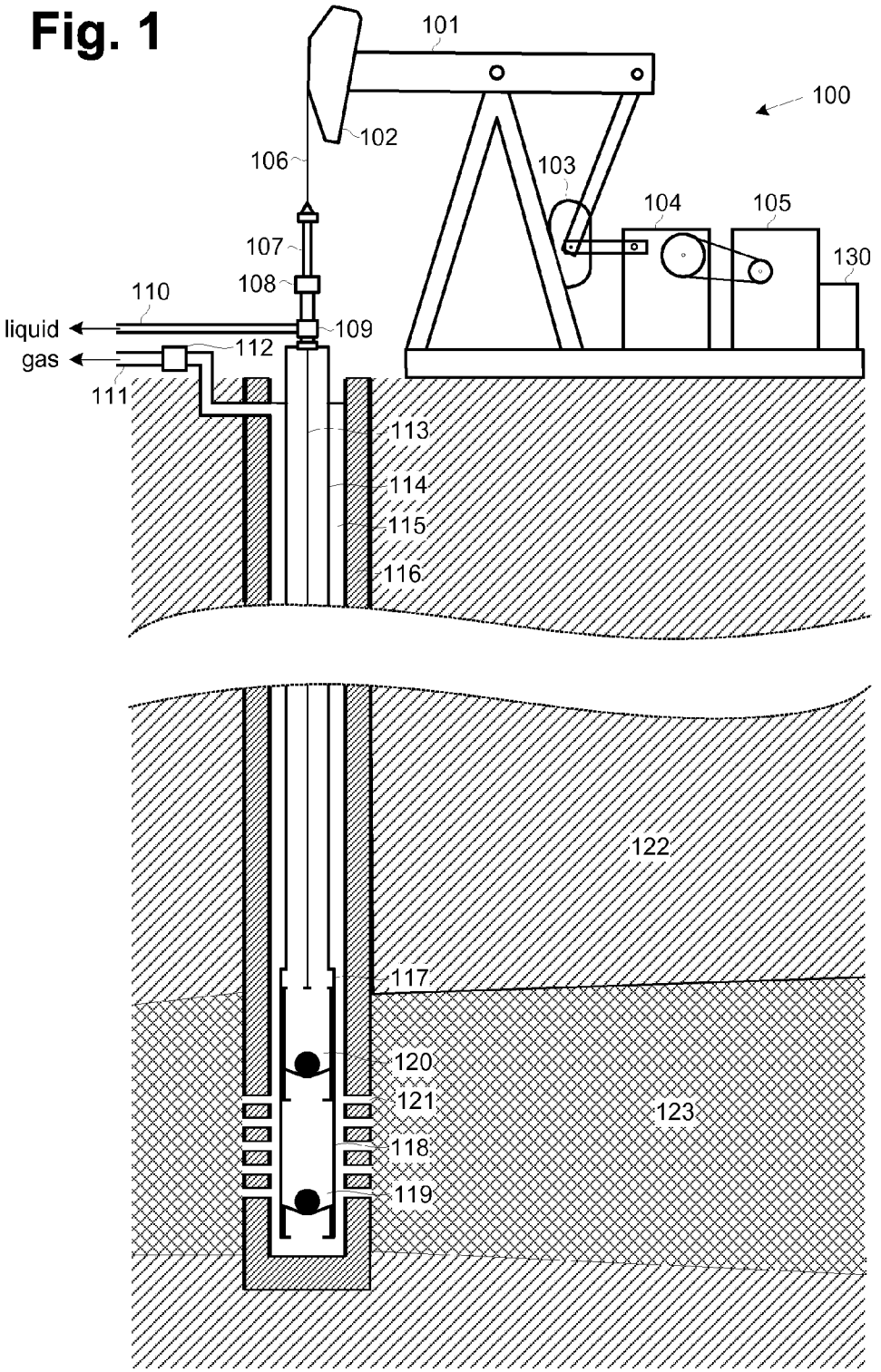


Fig. 1


101
100
102
106
103
104
105
107
130
108
110
liquid
109
gas
112
111
113
114
115
116
122
117
120
121
123
118
119

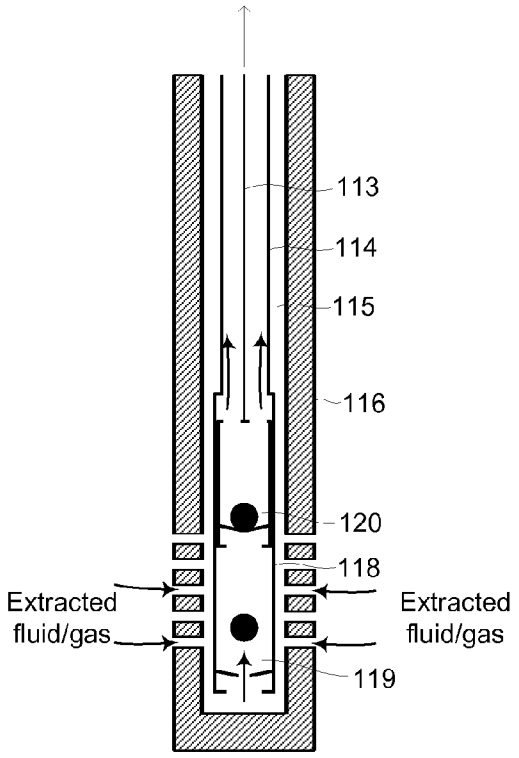

113
114
115
116
120
118
Extracted fluid/gas
Extracted fluid/gas
119

Fig. 2

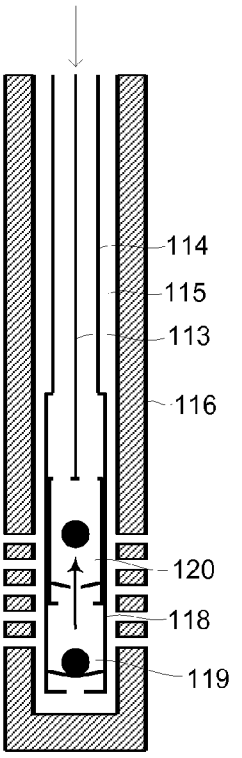

114
115
113
116
120
118
119

Fig. 3

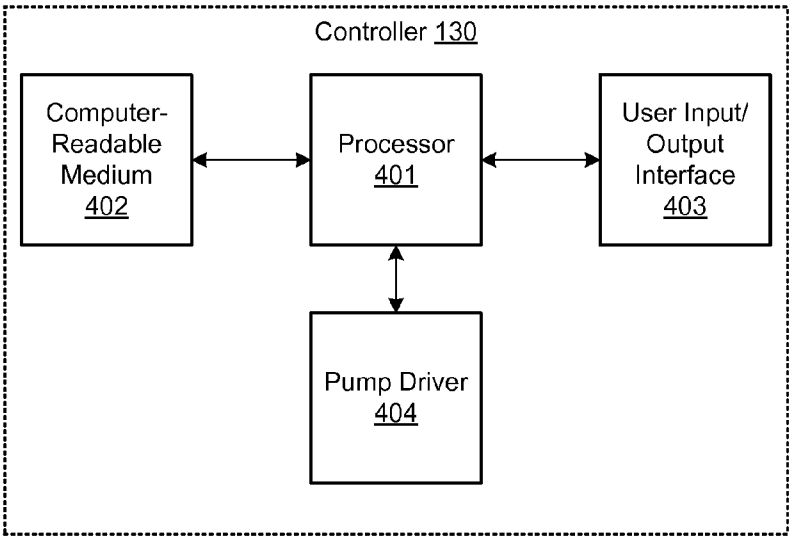

Controller 130
Computer-Readable Medium 402
Processor 401
User Input/ Output Interface 403
Pump Driver 404

Fig. 4

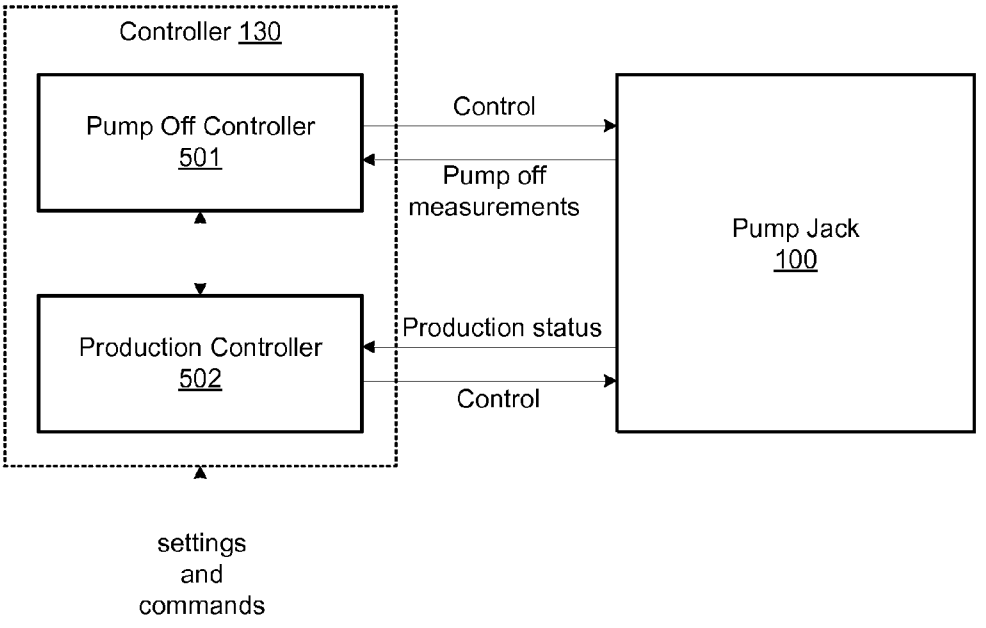

Controller 130
Pump Off Controller 501
Production Controller 502
Control
Pump off measurements
Production status
Control
Pump Jack 100
settings and commands

Fig. 5

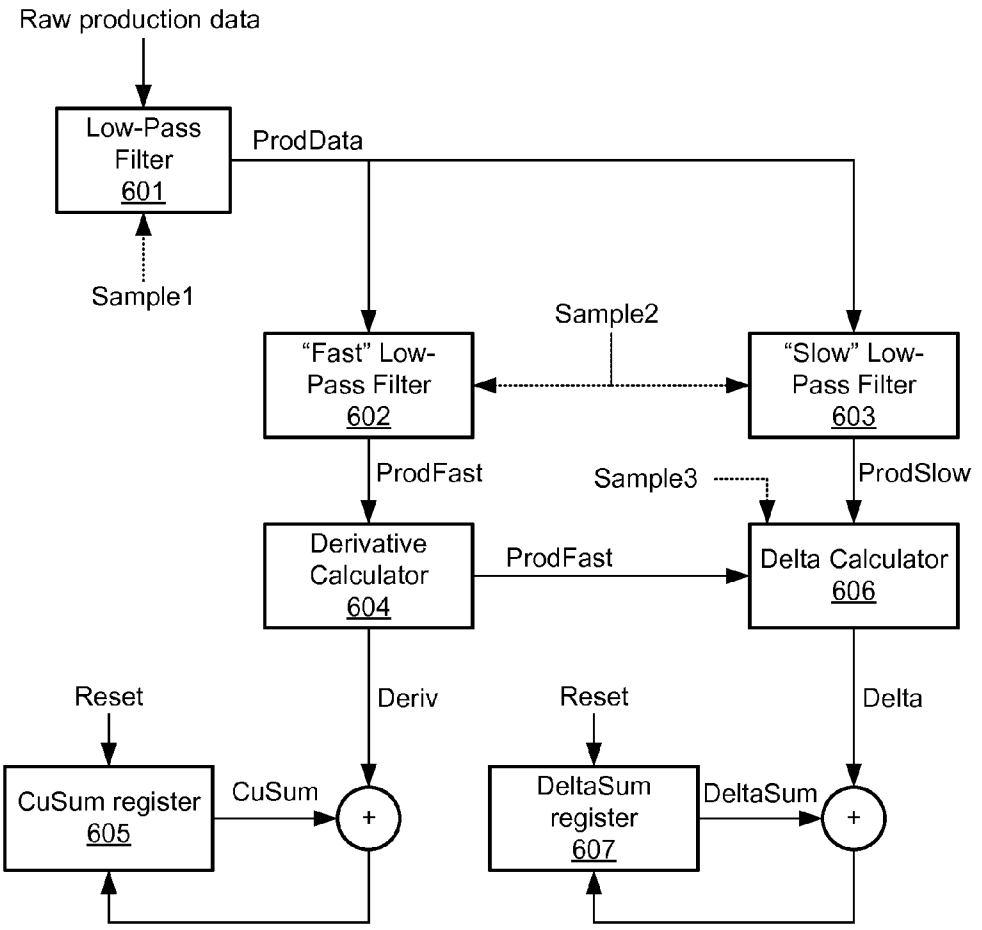

Raw production data
Low-Pass Filter 601
ProdData
Sample1
Sample2
"Fast" Low-Pass Filter 602
"Slow" Low-Pass Filter 603
ProdFast
Sample3
ProdSlow
Derivative Calculator 604
ProdFast
Delta Calculator 606
Reset
Deriv
Reset
Delta
CuSum register 605
CuSum
+
DeltaSum register 607
DeltaSum
+

Fig. 6

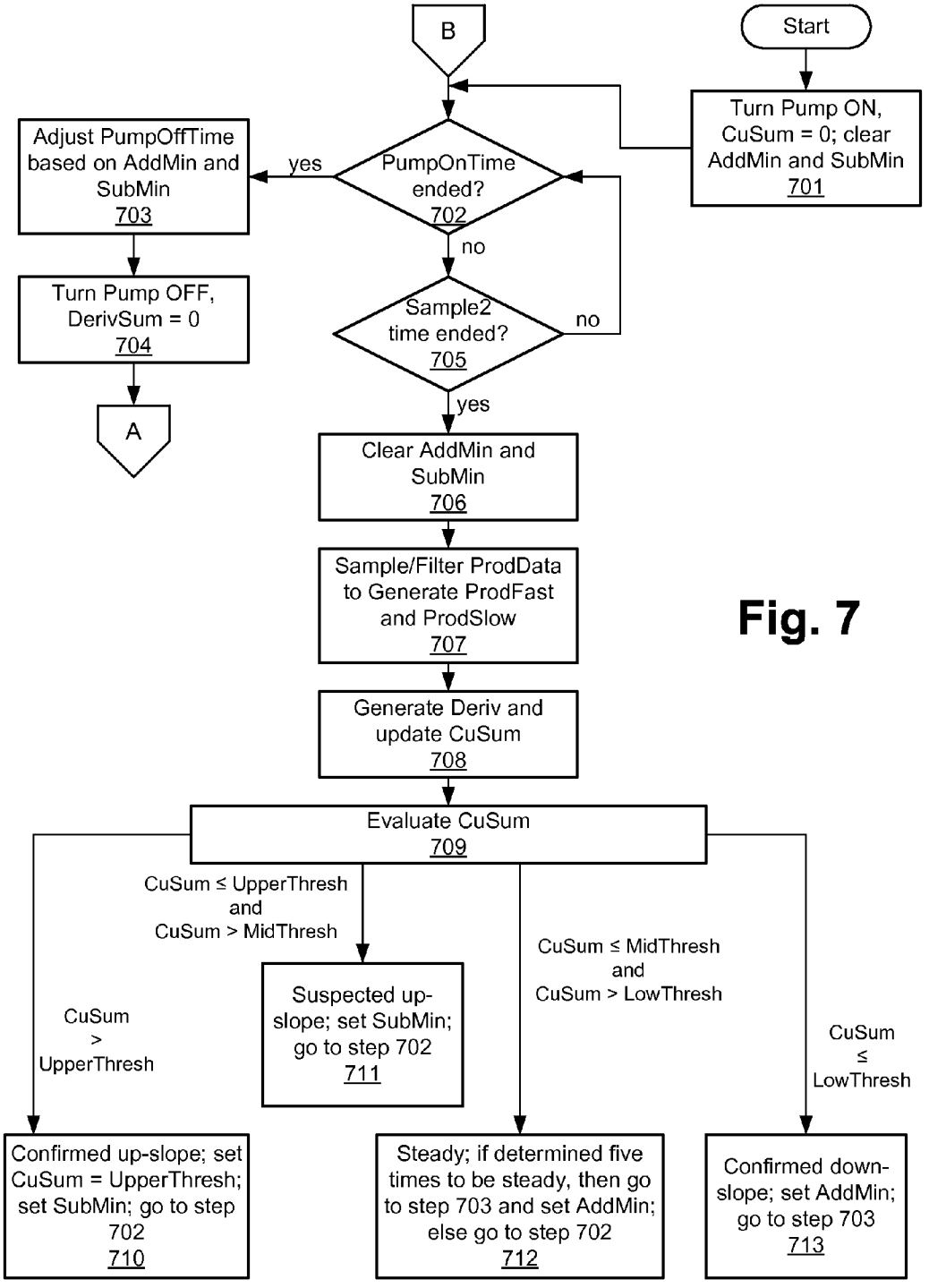

B
Start
Turn Pump ON, CuSum = 0; clear AddMin and SubMin 701
Adjust PumpOffTime based on AddMin and SubMin 703
yes
PumpOnTime ended? 702
no
Turn Pump OFF, DerivSum = 0 704
Sample2 time ended? 705
no
A
yes
Clear AddMin and SubMin 706
Sample/Filter ProdData to Generate ProdFast and ProdSlow 707
Generate Deriv and update CuSum 708
Evaluate CuSum 709
CuSum ≤ UpperThresh and CuSum > MidThresh
CuSum > UpperThresh
Suspected up-slope; set SubMin; go to step 702 711
CuSum ≤ MidThresh and CuSum > LowThresh
CuSum ≤ LowThresh
Confirmed up-slope; set CuSum = UpperThresh; set SubMin; go to step 702 710
Steady; if determined five times to be steady, then go to step 703 and set AddMin; else go to step 702 712
Confirmed down-slope; set AddMin; go to step 703 713

Fig. 7

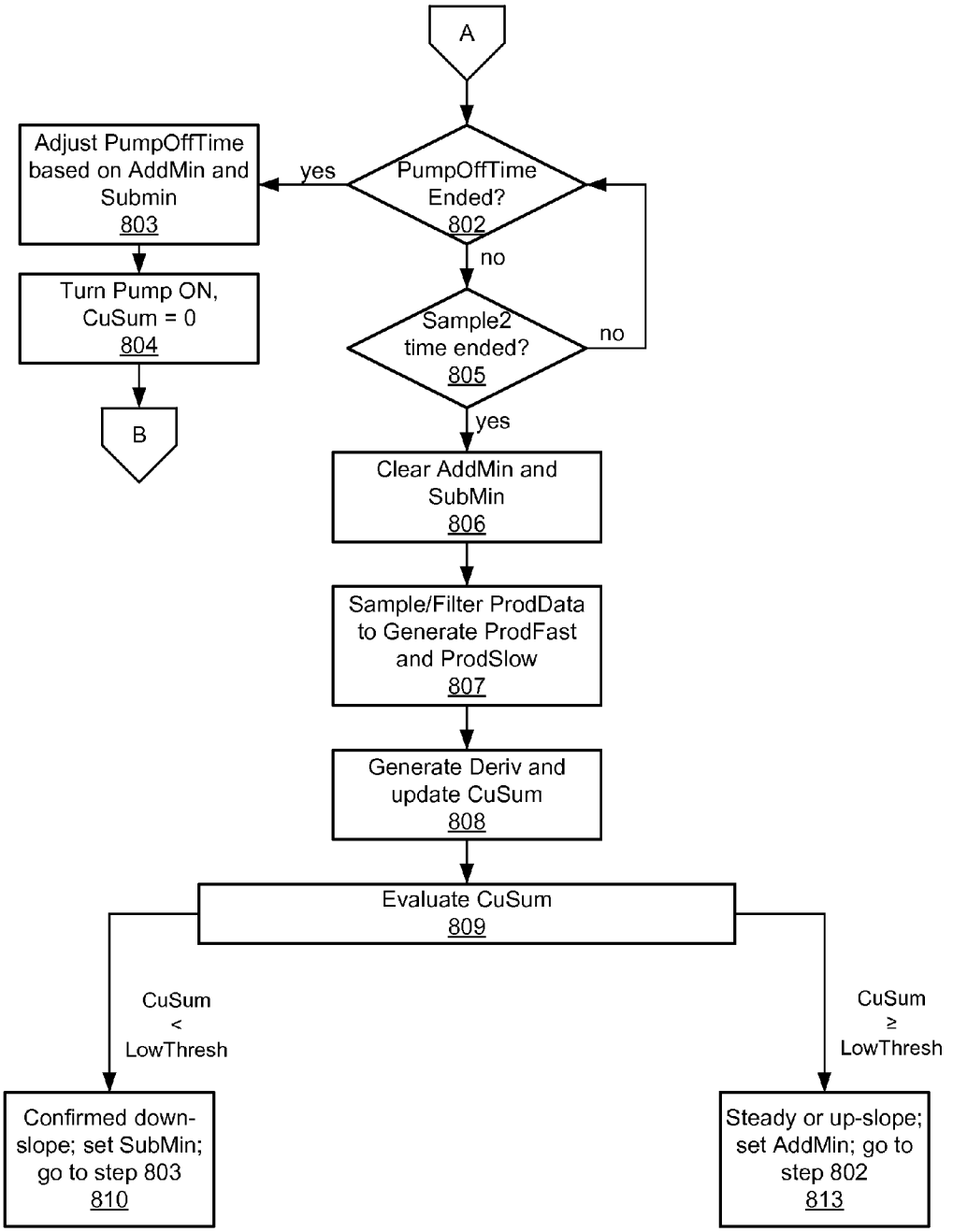

A
PumpOffTime Ended? 802
yes
Adjust PumpOffTime based on AddMin and Submin 803
Turn Pump ON, CuSum = 0 804
B
no
Sample2 time ended? 805
no
yes
Clear AddMin and SubMin 806
Sample/Filter ProdData to Generate ProdFast and ProdSlow 807
Generate Deriv and update CuSum 808
Evaluate CuSum 809
CuSum < LowThresh
CuSum ≥ LowThresh
Confirmed down-slope; set SubMin; go to step 803 810
Steady or up-slope; set AddMin; go to step 802 813

Fig. 8

PUMPJACK PRODUCTION CONTROL

BACKGROUND

Pumpjack systems often include a pump-off controller that switches a pump between an ON state and an OFF state based on how long the pump has been in a particular state. These pump-off controllers may also switch the pump to the OFF state when a pump-off condition is detected, such as an underfilled pump stroke. In some systems, the well is intended for producing gas, and the pump is used to remove largely undesirable liquid from the well (to make room for the gas to enter the well for extraction). In these types of wells, the pump may run regardless of whether liquid extraction at a given time is beneficial to gas production.

SUMMARY

Various aspects are described herein that may provide, for example, systems, methods, and software for controlling a pump, such as a pump that is configured to pump liquid out of a gas-producing well. The state of the pump may be controlled based on feedback information regarding the rate of a product being produced by the well. For example, where gas (e.g., natural gas) is being produced by the well, the pump may be switched between the ON state and the OFF state depending upon whether the production rate is determined to be increasing, decreasing, or steady. The switching of the pump from the OFF state to the ON state may also be based on a parallel decision based on whether a pump off condition has been reached. Moreover, the pump off time may be adjusted based on the determined production rate.

This type of pump control may allow for a system that is biased toward running the pump only when deemed necessary in accordance with the determined production rate. This may potentially allow for the system to be more efficient by not running the pump when it would likely not provide any benefit. This may be in contrast to simpler pump-off controllers that control the pump based merely on timers and/or on detected traditional pump-off conditions. Moreover, the proposed pump control may be used in conjunction with traditional time-based control and/or traditional pump-off condition-based control. In some cases, the additional control functionality may even be retrofitted to traditional pump-off controllers.

According to some aspects as described herein, example methods, software, and apparatuses are described for controlling a pump configured to pump liquid out of a well. Such control may involve, for example, determining whether a production rate of gas from the well is increasing, decreasing, or steady; determining whether the state of the pump should be changed depending upon whether the production rate of the gas is determined to be increasing, decreasing, or steady; and responsive to determining to that the pump should be switched, changing the state of the pump.

The techniques described herein may be utilized in connection with various types of pump systems, such as, but not limited to, a pumpjack system for pumping water and liquid oil, and for producing natural gas from a well.

These and other aspects of the disclosure will be apparent upon consideration of the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present disclosure and the potential advantages of various aspects described herein may be acquired by referring to the following description in consideration of the accompanying drawings, in which like reference numbers indicate like features, and wherein:

FIG. **1** is a cross-sectional view of an example pumpjack system;

FIG. **2** is a cross-sectional view of an example downhole pump in operation during an up stroke;

FIG. **3** is a cross-sectional view of an example downhole pump in operation during a down stroke;

FIG. **4** is a block diagram of an example controller that may be used to perform various functions;

FIG. **5** is another block diagram of an example controller, including a pump off controller and a production controller;

FIG. **6** is a block diagram of an example production data conditioner; and

FIGS. **7** and **8** are a flow chart showing example steps that may be performed to control a pump.

DETAILED DESCRIPTION

FIG. **1** is a cross-sectional view of an example pumpjack system **100**. Such a system **100** may include an above-ground structure that includes a walking beam **101** onto which a horse head **102** is mounted. Walking beam **101** may reciprocate so as to move horse head **102** upward (up stroke) and downward (down stroke) on a periodic basis. To move walking beam **101**, a controller **130** may command a prime mover **105** (such as a motor) to send rotational power to a transmission **104**, which may include a gear reducer that causes a crank arm and counter weight **103** to rotate at a reduced rotational speed and increased torque relative to prime mover **105**. Because counter weight **103** is offset from its rotational axis, this causes an arm attached to walking beam **101** to move walking beam **101** in a reciprocating manner.

As horse head **102** moves up and down, this causes a string **106** (also known as a birdie) that is usually made of a steel cable to also move up and down. In turn, this movement causes a polished rod **107** to move up and down through a lubricated stuffing box **108**, which in turn causes a sucker rod **113** (typically made of a series of longitudinally interconnected steel rods) attached to the lower end of polished rod **107** to also move up and down.

Sucker rod **113** extends downward into a well in ground **122**, through tubing **114** to a downhole pump **117**. A hollow annular region, referred to herein as annulus **115**, encircles tubing **114** and is disposed between tubing **114** and an outer casing **116**. Casing **116** includes a series of perforations **121** that expose annulus **115** to an oil or gas bearing region **123** of ground **122**. Liquids, such as oil and water, and gases, such as hydrocarbon gases (e.g., methane, ethane, etc.) enter perforations **121** into annulus **115** through a combination of outside pressure and a vacuum produced by downhole pump **117**. Liquids fall to the bottom of annulus **115** due to gravity, and gases (being lighter than the liquids) rise upward in annulus **115**.

Downhole pump **117** may include a standing valve **119**, a travelling valve **120** coupled to sucker rod **113**, and a hollow region referred to as a pump barrel **118** disposed between the standing and travelling valves **119**, **120**. Downhole pump **117** typically operates as follows. Referring to FIG. **2**, as sucker rod **113** moves in an up stroke, liquid above travelling valve **120** causes travelling valve **120** to close, and so the upward movement creating a vacuum between travelling valve **120** and standing valve **119**. This causes standing valve **119** to open, allowing liquid that has accumulated at the bottom of annulus **115** to be drawn up through standing valve **119**. Meanwhile, if tubing **114** is sufficiently already full of previously pumped liquids, then the liquid at the top of the liquid

stack in tubing **114** is pushed upward an outward through a junction **109** and an exit tube **110** for collection and/or disposal.

On the down stroke (FIG. **3**), sucker rod **113** moves downward, also causing travelling valve **120** to move downward. This produces a relatively higher pressure between travelling valve **120** and standing valve **119**, causing it to open and travel downward through the liquid that previously passed through standing valve **119** on the up stroke. The higher pressure also causes standing valve **119** to close, thereby forcing the previously-drawn liquid to remain in place while travelling valve **120** moves downward through that liquid. By alternating up and down strokes, downhole pump **117** may therefore draw liquids that have fallen to the bottom of annulus **115** up and out of the well.

As previously explained, while liquids fall to the bottom of annulus **115**, gases tend to rise upward in annulus **115**. Thus, depending upon the level of the liquid at the bottom of annulus **115** relative to the intake of downhole pump **117**, gases are ideally not pumped through downhole pump **117**. Instead, gases may be collected and/or disposed of from the well through an exit tube **111** disposed at or near the top of annulus **115**. A measurement device **112** may be coupled to exit tube **111** for measuring the volume and/or rate of the gas traveling through exit tube **111**.

Depending upon the desired product to be produced by the well, either the gas, or the liquid, or both the gas and the liquid may be considered a production product. Likewise, depending upon what is desired, the gas or the liquid may be considered a waste product. For example, depending upon where the well is located, the well may produce an excellent supply of oil, whereas the gas also produced may be an unwanted byproduct or it may be a useful product. In this case, downhole pump **117** may be used to pump the desirable oil (along with other liquids such as water). Or, where gas is considered the main product to be produced by the well, such as where the well is located in a region that contains little to no liquid petroleum product to be extracted, then the waste liquid may primarily include water (with various contaminants). In this case, the downhole pump **117** may be used to draw up the waste liquid simply to prevent annulus **115** from becoming full of the liquid and thereby preventing the desirable gas product from entering annulus **115**.

Pumpjack system **100** may operate continuously or on a periodic basis, under the control of controller **130**. For example, controller **130** may cause prime mover **105** to continuously run so as to cause pumpjack system **100** to perform a series of stroke cycles (each stroke cycle including a pair of an upstroke and a downstroke). Such continuous operation may carry on until a pump off condition occurs. A pump off condition may occur where, for instance, it is determined that there is insufficient liquid in annulus **115** to be pumped by downhole pump **117**. Continuing to pump under such a condition may result in conditions that can cause damage to the pumpjack system **100**. A pump off condition may also occur due to a timeout. For instance, controller **130** may be configured so as to continuously cause pumpjack system **100** to pump for X amount of time or until another pump off condition is met, whichever occurs first. In other examples, pumpjack system **100** may be controlled to perform only a single stroke cycle at a time, with a delay between cycles. In still further examples, pumpjack system **100** may be controlled to adjust the speed of a stroke. The stroke speed, continuous duration, stroke frequency, and/or delay between stroke cycles may be set so as to, ideally, minimize energy expended, minimize pumpjack system wear, and maximize production. All of these can depend upon a variety of factors. For example, if liquid is drawn through perforations **121** into annulus **115** very quickly and easily, then pumpjack system **100** may need to operate downhole pump **117** more often or on a more continuous basis. Otherwise, the liquid level in annulus **115** may rise too high, reducing the efficiency of the system especially where gas is the desired product (since there will be less room in annulus **115** for the gas). On the other hand, if liquid is not drawn quickly through perforations **121**, then the liquid level may be too low in annulus **115** unless pumping is reduced. As discussed above, this may allow gas to be pumped up through downhole pump **117**, potentially causing production loss, gas lock and/or equipment damage.

As can be seen, there is accordingly a level, or range of levels, at which the liquid level in annulus **115** should be maintained to provide a desired system efficiency. In an ideal world, one might directly measure the liquid level and control pumpjack system **100** based on the direct measurement. While such an arrangement has been proposed, this is not always practical, because downhole pump **117** may be located extremely deep into the earth and subject to intense environmental conditions, making the sensor, and maintenance thereof, expensive. Moreover, such an arrangement would involve finding a way for the remote underground sensor to communicate with the above-ground control system, thereby raising an additional challenge.

Another way to control a pumpjack is to measure the mechanical force experienced by certain system components over the duration of an upstroke and/or a downstroke. Force may be measured in a variety of ways, such as using a conventional downhole card inside the well and/or a dynamometer coupled to an above-ground portion of the pumpjack system. When the measured force is graphed against the displacement of the travelling valve of the downhole pump (or against the displacement of any other reciprocating or rotating portion of the pumpjack), such a graph results in a curve that is known to provide useful information about the conditions experienced by the downhole pump.

Another way to control a pumpjack is to measure the torque experienced by a component of the pumpjack such as the prime mover **105**. Torque may be measured in a variety of ways, such as using an ammeter on current fed to a prime mover **105** (if prime mover **105** is an electric motor). When the measured torque is graphed against the displacement of a reciprocating component of the pumpjack system such as the reciprocating polished rod **107**, such a graph results also in a curve that is known to provide information that may be used to estimate various conditions experienced by the pumpjack system **100**, such as pump fill and/or whether a pump-off condition exists.

Any of the functions and steps described herein may be performed and/or controlled by controller **130**. An example block diagram of controller **130** is shown in FIG. **4**. Controller **130** may be or otherwise include a computer, and may include hardware that is hard-wired to perform specific functions and/or hardware that may execute software to perform specific functions. The software, if any, may be stored on a non-transitory computer-readable medium **402** in the form of computer-readable instructions. Controller **130** may read those computer-readable instructions, and in response perform various steps as defined by those computer-readable instructions. Thus, for example, any of the steps and functionality described in connection with FIGS. **5-8** may be implemented, for example, by reading and executing such computer-readable instructions for performing such steps and implementing such functionality, and/or by any hardware subsystem (e.g., a processor **401**) from which controller **130**

is composed. Processor **401** may be implemented as, for example, a central processing unit (CPU), an application-specific integrated circuit (ASIC), a field-programmable gate array (FPGA), and/or a programmable logic controller (PLC). Additionally or alternatively, any of the above-mentioned functions may be implemented by the hardware of controller **130**, with or without the execution of software.

Computer-readable medium **402** may include not only a single physical non-transitory storage medium or single type of such medium, but also a combination of one or more such storage media and/or types of such media. Examples of computer-readable medium **402** include, but are not limited to, one or more memory chips, hard drives, optical discs (such as CDs or DVDs), magnetic discs, and magnetic tape drives. Computer-readable medium **402** may be physically part of, or otherwise accessible by, controller **130**, and may store computer-readable instructions (e.g., software) and/or computer-readable data (i.e., information that may or may not be executable).

Controller **130** may also include a user input/output interface **403** for receiving input from a user (e.g., via a keyboard, mouse, and/or remote control) and/or for providing output to the user (e.g., via display device, an audio speaker, and/or a printer). For example, user input/output interface **403** may be used to indicate pump ON or OFF status, time remaining until pump ON or OFF, pump fill, and/or any other desired information.

Controller **130** may further include a pump driver **404** for controlling whether prime mover **105** will operate to cause pumping action. For example, pump driver **404** may cause prime mover **105** to turn on and off as desired. In some embodiments, controller **130**, via pump driver **404**, may cause prime mover **105** to turn on or off, or otherwise adjust its operation, such as changing the speed of the pump (changing the stroke speed). As will be discussed, such pump control operations may be performed in response to a pump off condition and/or another factor such as the expiration of a timer and/or based on gas production rate.

FIG. **5** is another block diagram of an example controller, including a pump off controller **501** and a production controller **502**. Pump off controller **501** and production controller **502** may be physically separate units, or they may be integrated as a single controller with the functionality of both controllers **501**, **502**. For example, controller **130** may implement one or both of pump off controller **501** and production controller **502**. In some embodiments, pump off controller **501** and production controller **502** may utilize the same physical processor **401**, but may be implemented using different portions of the above-mentioned computer-executable instructions. In other embodiments, pump off controller **501** and production controller **502** may utilize different physical processors and/or other hardware, and may communicate with each other in a wired and/or wireless manner. In either case, if production controller **501** is already in operation in the field, rather than replace the entire controller **301**, production controller **502** may be retrofitted with production controller **502**, such as via a software upgrade to controller **103** and/or as a hardware addition to controller **103**.

Pump off controller **501** may be configured to control the ON and OFF states of pump jack system **100** in response to one or more measurements relevant to a pump off condition, and/or responsive to the expiration of a timer. For instance, pump off controller **501** may be configured to turn the pump ON until either a pump off condition is detected or a timeout occurs, whichever occurs first. Examples of measurements that may be relevant to a pump off condition include, as discussed previously, torque and/or force measurements.

Production controller **502** may be configured to modify the operation of the pump based on actual production measurements. This may be done in various ways. For example, production controller **502** may provide an input to pump off controller **501**, which may cause pump off controller **501** to modify how it controls the pump. Alternatively, production controller **502** may directly control the pump. In the latter case, commands from pump off controller **501** and production controller **502** to the pump may be arbitrated in the event of conflicting commands. For example, a command to turn or maintain the pump OFF by either of the controllers **501**, **502** may take precedence over a command to turn or maintain the pump ON. Or, a command to turn or maintain the pump ON by either of the controllers **501**, **502** may take precedence over a command to turn or maintain the pump OFF.

At a high level, pump off controller **501** and production controller **502** together (e.g., as controller **130**) may operate, for example, as shown below in Table 1. This example assume that the production product is gas (e.g., natural gas), and that downhole pump **117** is used mostly for removing waste products (e.g., water and other liquids) from annulus **115** to make room for the desirable natural gas to enter annulus **115** and rise upward for collection. While the waste products may themselves include one or more desirable products, such as oil, for the present example it will be assumed that production refers only to the gas that is produced for collection.

TABLE 1

Pump Status	Production	Pump Control Action	OFF Time Adjustment
ON	steady	stay ON, unless production is consistent for threshold time; otherwise turn pump OFF	increase
	increasing	stay ON	decrease
	decreasing	turn pump OFF	increase
OFF	steady	stay OFF, unless maximum OFF time is reached	increase
	increasing	stay OFF, unless maximum OFF time is reached	increase
	decreasing	turn pump ON	decrease

The example operation according to Table 1 is arranged such that the system is biased to maintain production while not expending energy (by operating the pump) unless it is deemed necessary. In comparison with a simple ON/OFF time pump off controller, utilizing the above operating principle may result in a relative increase in production, and possibly a relative decrease in energy expenditure, or at least a relatively small increase in energy expenditure compared with the increase in production. Variations on the operating characteristics of Table 1 may be used, while still achieving increased production in an efficient manner.

Studying the example of Table 1 more closely, it will be seen that the pump is turned to (or maintained in) an ON state only if the ON state is apparently benefitting production. That is, if gas production is increasing while the pump is in the ON state, the system will maintain the ON state in the hope that this will continue to cause production to increase, at least for some period of time. And, if production is steady (e.g., relatively constant, such as within an upper and lower threshold, or having a very small slope), then the pump may remain ON (because it can be assumed that the status quo may be helping

to maintain production). However, if production is steady for an extended period of time, then the pump may be turned OFF.

Likewise, if the pump is in the OFF state, then according to Table 1, the system would be reluctant to turn the pump ON unless the OFF state is associated with decreasing production. Thus, there is a bias in this example to maintain the pump in an OFF state unless it is deemed likely that the ON state would benefit production.

Another potential consequence of operating the system in accordance with the above operating principle (e.g., Table 1), is that the level of the liquid at the bottom of annulus **115** may be naturally maintained at a level resulting in high production, and possibly even optimal production for the operating conditions. This may mean that the level of the liquid may be generally located somewhere between the intake of downhole pump **117** and the bottom of perforations **121**. For instance, depending upon the particular operating conditions, this operating principle may be expected to potentially result in the liquid level being maintained very close to the bottom of perforations **121**. This may be in contrast to many systems using a simple conventional pump off controller, in which the liquid level is typically maintained very close to the intake of downhole pump **117**.

Production data for use with Table 1 may be collected by, e.g., measurement device **112**. While the raw production data may be used directly to determine whether production is steady, increasing, or decreasing, it may be desirable for various reasons to pre-process, or condition, the production data. For instance, the raw production data may be highly variable over short periods of time, which may cause the control system to act in an unstable manner.

FIG. **6** is a block diagram of an example production data conditioner that may generate indicators based on the raw production data. The indicators, rather than the raw production data, may be used to determine whether production is steady, increasing, or decreasing. In the example of FIG. **6**, it is assumed that the raw production data is an analog signal, as opposed to digital data. However, the raw production data may be digital data. The raw production data may be produced and/or sampled on a periodic basis.

The raw production data may be filtered by a low-pass filter **601** to generate a data signal referred to herein as ProdData. Low-pass filter **601** produces ProdData at a sampling period referred to herein as Sample**1**, which may have a sampling period appropriate for the sensor and overall system design of, e.g., less than one second (e.g., twenty milliseconds), or some number of seconds. Again, all time periods discussed herein are merely examples.

Next, ProdData may be filtered by two parallel low-pass filters **602** and **603**. Low-pass filter **602** is referred to herein as a "high-cutoff" low-pass filter, and low-pass filter **603** is referred to herein as a "low cutoff" low-pass filter. The "high-cutoff" and "low-cutoff" designations are relative and refer to how much of the higher-frequency components are suppressed by the filters—the "low-cutoff" low-pass filter **603** suppresses more higher-frequency components (has a narrower passband) than the "high-cutoff" low-pass filter **602**. Each of these filters **602**, **603** produce a data signal at a sampling rate of Sample**2**, which may be equal to or longer than Sample**1**. For example, where the period of Sample**1** is twenty milliseconds, the period of Sample**2** may be one or more orders of magnitude longer than Sample**1**, such as one minute or longer. The output data signal of "high-cutoff" low pass filter **602** is referred to herein as ProdFast, and the output data signal of "low-cutoff" low pass filter **603** is referred to herein as ProdSlow, each of which may include a Sample**2** period series of data. ProdSlow may represent a filtered version of the raw production data that, relatively speaking, does not readily respond to variations in the raw production data. Thus, ProdSlow may be considered to generally represent a short-term average baseline value of the production data. ProdFast, on the other hand, may represent a filtered version of the raw production data, but one that responds more readily to higher-frequency variations in the raw production data (while still suppressing much higher frequency variations that may represent noise or anomalies).

Next, a derivative calculator **604** may be used to calculate the derivative of ProdFast, and to output the calculated derivative as a data signal referred to herein as Deriv. In alternative embodiments, derivative calculator **604** may not take a true derivative, but instead may calculate another type of delta value. ProdSlow, in the meantime, may be processed by a delta calculator **606** to calculate a delta, which may be calculated, for example, as follows: Delta=100×(ProdFast−ProdSlow)/ProdSlow. The resulting data signal Delta may be considered to generally represent a short-term change from the average baseline value represented by ProdSlow.

Next, Deriv is accumulated over time, and the accumulated value CuSum is stored in a register referred to herein as CuSum register **605**. Likewise, Delta is also accumulated over time, and the accumulated value DeltaSum is stored in a register referred to herein as DeltaSum register **607**. As will be discussed below, CuSum and/or DeltaSum may be used as indicators from which decisions may be made as to whether production is currently steady, increasing, or decreasing.

FIGS. **7** and **8** are a flow chart showing example steps that may be performed to control a pump, and may operate based on the values of CuSum and/or DeltaSum. The process of FIG. **7** may be performed while the pump is in the ON state, and the process of FIG. **8** may be performed while the pump is in the OFF state.

Referring first to FIG. **7**, pumpjack system **100** (and/or controller **130**) may be turned on or otherwise started, at which time the process of FIG. **7** may begin at step **701**. At step **701**, the pump may be turned on (such as by controlling prime mover **105**) to the ON state, and CuSum may be cleared by setting it to zero. In addition, one or more flags indicating whether a pump off time should be increased or decreased may be cleared. In the example embodiment of FIG. **7**, a flag called AddMin, when set, may indicate that the pump off time should be increased, such as by one minute or another period of time, and another flag called SubMin, when set, may indicate that the pump off time should be decreased, such as by one minute or another period of time. The pump off time would be the amount of time that the pump would remain in an OFF state, as monitored by a timer. The value of the pump off time is referred to herein as PumpOffTime. In alternative embodiments, AddMin and SubMin may be embodied as a single flag, where one value representing increasing the pump off time and another value represents decreasing the pump off time.

There may also be a defined pump on time, monitored by a timer and represented in this case by the value PumpOnTime. At step **702**, it may be determined whether PumpOnTime has ended or expired, and if so, then at step **703**, PumpOffTime is increased or decreased, e.g., by one minute, depending upon whether AddMin or SubMin is set. At step **704**, the pump is turned OFF and CuSum is cleared again by setting it to zero. The process would then move to FIG. **8**, which will be discussed later below.

If, at step **702**, it is determined that PumpOnTime has not yet ended, then the process may move to step **705**, in which it is determined whether the current Sample**2** period has ended.

As discussed previously, Sample**2** refers to the time period at which the data series of ProdFast and ProdSlow are generated. Sample**2** may be, for example, one minute. If the current Sample**2** period has not ended, then the process cycles back to step **702**.

Once it is determined at step **705** that Sample**2** has ended, the process moves to step **706** and clears AddMin and SubMin. Also, at step **707**, a new value of each of ProdFast and ProdSlow is generated, and at step **708**, Deriv is generated and CuSum is updated with the most recent value of Deriv, by adding the most recent value of Deriv to the previous value of CuSum.

Next, at step **709**, the value of CuSum may be evaluated and compared with one or more thresholds. The result of this evaluation may determine whether production is considered to be in one of four states: confirmed up-slope (confirmed increasing), suspected up-slope (suspected increasing), steady zone, and confirmed down-slope (confirmed decreasing). The thresholds may include an upper threshold referred to herein as UpperThresh, a middle threshold referred to herein as MidThresh, and a lower threshold referred to herein as LowThresh. The threshold values may be set to any values as desired. In one example, UpperThresh may be equal to 5.0, MidThresh may be equal to 2.5, and LowThresh may be equal to −10.0. However, these values are merely examples and should not be considered as limiting to the present invention.

If it is determined that CuSum is greater than UpperThresh, then it may be concluded that there is a confirmed up-slope in production. In this case, at step **710**, CuSum may be set equal to UpperThresh, the SubMin flag may be set (indicating a desire to reduce the amount of PumpOffTime, such as by one minute), and the process may move to step **702**. The pump remains ON for now, because the assumption is that the current pump state (ON) is benefitting production.

If it is determined that CuSum is greater than MidThresh and CuSum is less than or equal to UpperThresh, then it may be concluded that there is a suspected up-slope in production. In this case, at step **711**, the SubMin flag may be set (indicating a desire to reduce the amount of PumpOffTime, such as by one minute), and the process may move to step **702**. The pump remains ON for the time being, because the assumption is that the current pump state (ON) is benefitting production.

If it is determined that CuSum is greater than LowThresh and CuSum is less than or equal to MidThresh, then it may be concluded that production is currently steady. In this case, at step **712**, the process may move to step **702** unless this is the fifth time in a row that step **712** has been executed (i.e., that it has been concluded that production is steady). This implies that production is neither improving nor declining while the pump is running If that is the case, then AddMin may be set (indicating a desire to increase the amount of PumpOffTime, such as by one minute) and the process may instead move to step **703**, thereby also causing the pump to change to the OFF state at step **704**. The pump is turned OFF because the assumption is that running the pump is not necessarily helping production, and running the pump at this point may not result in a sufficient increase in production to justify running pump. Thus, continuing to run the pump may be considered a waste of energy and may incur unnecessary wear and tear on the pump apparatus.

If it is determined that CuSum is less than or equal to LowThresh, then it may be concluded that there is a confirmed down-slope in production. In this case, at step **713**, the AddMin flag may be set, and the process may move to step **703**, thereby also causing the pump to change to the OFF state at step **704**. Again, the assumption here is that running the pump is not helping production, so the pump is turned off to avoid unnecessarily expending energy.

Thus, while the pump is ON, if production is deemed to be decreasing or is deemed to be steady over a sufficient period of time, then the process may cause the pump to turn OFF. Otherwise, the pump remains ON. This is consistent with the example of Table 1.

Once the pump is turned OFF at step **704**, the process may move to step **802** of FIG. **8**. At step **802**, it may be determined whether PumpOffTime has ended or expired, and if so, then at step **803**, PumpOffTime is increased or decreased, e.g., by one minute, depending upon whether AddMin or SubMin is set. At step **804**, the pump is turned ON and CuSum is again cleared by setting it to zero. The process would then move back to step **702** of FIG. **7**, which has already been discussed.

If, at step **802**, it is determined that PumpOffTime has not yet ended, then the process may move to step **805**, in which it is determined whether the current Sample**2** period has ended. If the current Sample**2** period has not ended, then the process cycles back to step **802**.

Once it is determined at step **805** that Sample**2** has ended, the process moves to step **806** and clears AddMin and SubMin. Also, at step **807**, a new value of each of ProdFast and ProdSlow is generated, and at step **808**, Deriv is generated and CuSum is updated with the most recent value of Deriv, by adding the most recent value of Deriv to the previous value of CuSum.

Next, at step **809**, the value of CuSum may be evaluated and compared with one or more thresholds. The result of this evaluation may determine whether production is considered to be in one of two states: (1) confirmed down-slope and (2) steady or confirmed up-slope.

If it is determined that CuSum is less than LowThresh, then it may be concluded that there is a confirmed down-slope in production. In this case, at step **810**, the SubMin flag may be set and the process may move to step **803**, such that the pump is turned back ON at step **804**. This is because the assumption is that the OFF state of the pump is harming production.

If it is determined that CuSum is greater than or equal to LowThresh, then it may be concluded that production is either steady or has a confirmed up-slope. In this case, at step **813**, the AddMin flag may be set and the process may move to step **802**. The pump remains OFF for now, because the assumption is that leaving the pump OFF is not harming production, and that expending additional energy to run the pump may not be expected to result in a sufficient increase in production.

Thus, while the pump is OFF, if production is deemed to be decreasing, then the process may cause the pump to turn ON. Otherwise, the pump remains OFF. This is consistent with the example of Table 1.

In addition to the above-discussed process of FIG. **8**, a parallel process may run in which DeltaSum and/or Delta may be evaluated periodically, say every five Sample**2** periods (e.g., every five minutes). If it is determined that Delta is less than LowThresh and/or DeltaSum is less than LowThresh, then PumpOffTime may be immediately reduced (shortened) by a greater amount than would be caused by setting SubMin (e.g., by five minutes). If this shortening of PumpOffTime causes PumpOffTime to be less than or equal to zero, then this may cause the process to immediately jump to step **804**, such that the pump is immediately turned ON. Otherwise, the process continues in its current state.

If the immediate reduction in PumpOffTime causes the process to jump to step **804** (thus turning on the pump) at least a predetermined number of times in a row (e.g., three times in

a row), then the conclusion may be that the process is not helping, and that possibly ProdSlow is not keeping up with current baseline values. In this case, ProdSlow may be set equal to ProdFast, and the process of FIGS. **7** and **8** continued.

In the above discussion with regard to FIGS. **7** and **8**, the process may alternatively be implemented in which one or more of the less-than conditions may be replaced with less-than-or-equal-to conditions and/or vice-versa, and/or one or more of the greater-than conditions may be replaced with greater-than-or-equal-to conditions and/or vice-versa. In addition, while particular examples methods of determining whether the production rate is increasing, decreasing, or steady have been described, such a determination may be performed in any of a number of ways, and may even involve a direct evaluation of the raw production signal without the above-described pre-processing of FIG. **6**, or using a different type of pre-processing. Moreover, there are many other ways of implementing the actions set forth in example Table 1.

In addition, while the above examples have assumed that the pump may change between a single ON state and a single OFF state, in further embodiments the pump may be controlled by controller **130** to have multiple speeds (e.g., multiple ON states). In such embodiments, where the process calls for changing the state of the pump from an ON state to an OFF state, the process may instead changing the state of the pump by reducing the speed of the pump. And, where the process calls for changing the state of the pump from an OFF state to an ON state (and where in these embodiments the pump had been previously slowed rather than actually turned OFF), the process may instead change the state of the pump by increasing the speed of the pump.

Moreover, any or all of the functions and steps described herein with regard to FIGS. **6-8** may be performed in whole or in part by controller **130**. Any of the blocks and steps of FIG. **6-8** may be implemented as software modules (e.g., in the form of computer-readable instructions) and/or as hardware, such as circuitry, of controller **130**. Moreover, some or all of the functions and steps of FIGS. **6-8** may be performed by production controller **502** of controller **130** and/or by pump off controller **501** of controller **130**.

Thus, various example systems, methods, and software have been described that may be used to control the production efficiency of a pumpjack or other pumping system, using as a feedback mechanism information about the actual current and/or past production. While embodiments of the present invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the present invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the present disclosure.

The invention claimed is:

1. A method of controlling a pump configured to pump liquid out of a well, comprising:

determining, by a computer, a plurality of production rates of gas from the well;

calculating at least one derivative of data representing the plurality of production rates of the gas;

using the at least one derivative to determine whether the plurality of production rates of the gas are decreasing or increasing;

changing a state of the pump responsive to determining to that a first one of the plurality of production rates of the gas is decreasing; and

maintaining the state of the pump responsive to determining that a second one of the plurality of production rates of the gas is increasing.

2. The method of claim **1**, further comprising changing a pump off time of the pump responsive to the determining that the first one of the plurality of production rates of the gas is decreasing.

3. The method of claim **2**, wherein the changing the state of the pump comprises changing the state of the pump from an OFF state to an ON state and the changing the pump off time comprises decreasing the pump off time.

4. The method of claim **2**, wherein the changing the state of the pump comprises changing the state of the pump from an ON state to an OFF state and the changing the pump off time comprises increasing the pump off time.

5. The method of claim **1**, wherein the state of the pump is OFF, and wherein the method comprises maintaining the pump in the OFF state responsive to the determining that the second one of the plurality of production rates of the gas is increasing and responsive to determining that the pump has remained in the OFF state for less than a predetermined amount of time.

6. The method of claim **1**, further comprising measuring the plurality of production rates of the gas.

7. A method of controlling a pump configured to pump liquid out of a well, comprising:

determining, by a computer, whether a production rate of gas is increasing, decreasing, or steady;

determining, by the computer, what state the pump should be in according to the following:

(1) while the pump is in an ON state and the production rate of the gas is determined to be steady, maintain the pump in the ON state and increase a pump off time of the pump,

(2) while the pump is in the ON state and the production rate of the gas is determined to be increasing, maintain the pump in the ON state and decrease the pump off time of the pump,

(3) while the pump is in the ON state and the production rate of the gas is determined to be decreasing, switch the pump to an OFF state and increase the pump off time of the pump,

(4) while the pump is in the OFF state and the production rate of the gas is determined to be steady, maintain the pump in the OFF state and increase the pump off time of the pump,

(5) while the pump is in the OFF state and the production rate of the gas is determined to be increasing, maintain the pump in the ON state and increase the pump off time of the pump, and

(6) while the pump is in the OFF state and the production rate of the gas is determined to be decreasing, switch the pump to the ON state and decrease the pump off time of the pump; and

responsive to determining to that the state of the pump should change between the ON state and the OFF state, changing the state of the pump between the ON state and the OFF state.

8. A method of controlling a pump configured to pump liquid out of a well, comprising:

measuring a production rate of gas from the well;

determining, by a computer, whether the production rate of the gas is increasing, decreasing, or steady;

increasing a pump off time of the pump responsive to determining that the production rate of the gas is steady;

determining, after said increasing, whether the production rate of the gas remains steady for at least a predetermined period of time; and

responsive to determining that the production rate of the gas has remained steady for at least the predetermined period of time, changing a state of the pump.

9. The method of claim **8**, further comprising:

responsive to said determining that the production rate of the gas is steady and prior to said changing the state of the pump, maintaining a state of the pump to be a same state as when the production rate of the gas was measured during said measuring.

10. The method of claim **8**, wherein the changing the state of the pump comprises hanging the state of the pump from an ON state to an OFF state.

11. The method of claim **8**, wherein said determining the production rate of the gas comprises filtering data representing measured gas production through a low-pass filter.

12. The method of claim **8**, wherein said determining whether the production rate of the gas is increasing, decreasing, or steady comprises comparing the production rate of the gas to an upper threshold value and a lower threshold value.

13. A method of controlling a pump configured to pump liquid out of a well, comprising:

receiving a first signal representing a measured production rate of gas from the well; and

filtering the first signal using a first low-pass filter to obtain a second signal,

filtering the first signal using a second low-pass filter having filter characteristics different from the first low-pass filter to obtain a third signal;

determining, by a computer, using both the second signal and the third signal, a plurality of directions of change of the production rate of gas;

responsive to determining that a first one of the plurality of directions of change is an increasing direction while the pump is in an ON state, decreasing a pump off time of the pump; and

responsive to determining that a second one of the plurality of directions of change is a decreasing direction while the pump is in the ON state, switching the pump to an OFF state and increasing the pump off time of the pump.

14. The method of claim **13**, further comprising:

responsive to determining that the first one of the plurality of directions of change is the increasing direction while the pump is in the OFF state, increasing the pump off time of the pump, and

responsive to determining that the second one of the plurality of directions of change is the decreasing direction while the pump is in the OFF state, switching the pump to the ON state and decreasing the pump off time of the pump.

15. The method of claim **14**, further comprising switching the pump from the OFF state to the ON state responsive to determining that the pump off time of the pump has expired.

16. The method of claim **14**, wherein the increasing the pump off time of the pump comprises increasing the pump off time after the pump off time has expired.

17. The method of claim **14**, wherein the switching the pump to the ON state comprises switching the pump to the ON state before the pump off time has expired.

18. The method of claim **13**, further comprising:

responsive to determining that a third one of the plurality of directions of change is neither the increasing direction nor the decreasing direction, increasing the pump off time of the pump.

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